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## KPI and LCA evaluation of integrated microwave technology for high temperature processes

C. Dorn<sup>a,\*</sup>, R. Behrend<sup>a</sup>, D. Giannopoulos<sup>b</sup>, L. Napolano<sup>c</sup>, B. García Baños<sup>d</sup>, V. James<sup>c</sup>, V. Uhlig<sup>a</sup>,  
J. M. Catalá<sup>d</sup>, M. Founti<sup>b</sup>, D. Trimis<sup>c,a</sup>

<sup>a</sup>*Institute of Thermal Engineering, TU Bergakademie Freiberg, Gustav-Zeuner-Str. 7, Freiberg 09599, Germany*<sup>b</sup>*School of Mechanical Engineering, National Technical University of Athens, Heroon Polytechniou 9, Athens 15780, Greece*<sup>c</sup>*STRESS S.c.a.r.l., vico II S.Nicola alla Dogana 9, Napoli 80133, Italy*<sup>d</sup>*Instituto ITACA, Universidad Politécnica de Valencia, Camino de Vera s/n., Valencia 46022, Spain*<sup>e</sup>*Division of Combustion Technology, Engler-Bunte-Institute, Karlsruhe Institute of Technology, Engler-Bunte-Ring 1, Karlsruhe 76131, Germany*

\* Corresponding author. Tel.: +49-3731-39-4387; fax: +49-3731-39-3942. E-mail address: [corina.dorn@iwtt.tu-freiberg.de](mailto:corina.dorn@iwtt.tu-freiberg.de)

### Abstract

Nearly a quarter of the energy consumption of Europe is required for industrial processes. Huge efficiency potentials can be exploited. One such is under research within the EU funded project DAPhNE by developing an integrated solution for energy intensive firing processes with microwave technologies. A methodology towards the preliminary definition of Key Performance Indicators (KPIs) with focus on economical, environmental and operational aspects is presented within this paper. By means of lab-scale measurements, the preliminary selected KPIs are determined and benchmarked against conventional KPIs to develop an eco-efficient production system. Moreover life cycle assessment (LCA) results support the evaluation and quantify the environmental benefits of microwave heating. Lab-scale results indicate a high carbon emission reduction potential.

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**Keywords:** Microwave; High temperature process; Experimental results; Key Performance Indicator; Life Cycle Assessment

### 1. Introduction

Nearly a quarter of the energy consumption of Europe is required for industrial processes [1]. In terms of reducing the industrial consumption for energy intensive firing processes, microwave (MW) heating offers a promising opportunity. Nowadays, MW heating is a well established heating technique for many industrial sectors with low temperature processes (i.e. drying) and low power demand. However, high temperature MW heating has not yet been implemented for full-scale industrial processes. Such an integrated MW solution is under development in the frame of the EU funded project DAPhNE. It brings together three manufacturing sectors (ceramic, glass and cement) with common concerns in relation to the energy consumption of their firing processes,

seeking common solutions by implementing high temperature MW technologies within an innovative approach.

Owing to the project objective, performance indicators are required that mainly focus on economic, environmental and operational perspectives, while the social performance assessment is not a priority. Consequently, the large number of available Key Performance Indicators (KPIs) related to the general manufacturing sector is limited to a shortlist of KPIs eligible to the three conventional (CONV) manufacturing sectors within the DAPhNE concept. The paper introduces a new approach towards developing and quantifying KPIs for energy intensive industrial processes. For evaluation purposes a MW lab-scale prototype is developed and a short technical overview is given. The lab-scale results support the analysis by determining relevant KPIs, which are used to benchmark the newly developed MW processes against the CONV ones.

Previous studies do not deal with methodologies based on KPIs and Life Cycle Assessment (LCA) and concerning MW technologies for high-temperature applications. The scope of this paper is the introduction of a new KPI methodology supported by experiments and LCA based modeling. The results are presented and discussed to evaluate and quantify the environmental benefits of the newly developed MW technology and to develop an eco-efficient production system.

## 2. Description of KPI methodology

The methodology followed to determine preliminary KPIs appropriate for the new MW concept is carried out in three stages. Starting from the vast amount of KPIs for the manufacturing sector in general (1st stage), a first shortlist of candidate KPIs is compiled, containing only KPIs already present in relevant reports in the cement, glass and ceramic industry (2nd stage). The preliminary definition of relevant KPIs (3rd stage) is achieved by adapting the shortlist of the candidate KPIs to the expected MW results. Moreover, the results fall into three major categories related to lower cost (economic aspect), emission reduction (environmental aspect) and operational benefits (operational aspect). In accordance with annual sustainability reports of relevant manufacturing companies [2-4], a set of 16 KPIs (approximately five for each result category) is considered to be a representative and adequate number of indicators for assessing the manufacturing process performance (see Table 1).

These KPIs are selected and adapted to the project requirements in such a manner to reflect clearly the economic, environmental and operational performance of the processes, thus enabling a direct comparison between the conventional and the corresponding MW processes.

Table 1: Preliminary Key Performance Indicators (KPIs).

KPI No.	Proposed Economic KPI	Unit
1	Specific Energy Cost (Electricity)	€/t of product
2	Specific Energy Cost (Fuel)	€/t of product
3	Specific Material Cost	€/t of product
4	Maintenance & Repair Cost	€/t of product
5	Total Cost of Ownership (TCO)	€
KPI No.	Proposed Environmental KPI	Unit
6	Specific net CO <sub>2</sub> emissions	kg/t of product
7	Specific Dust emissions	kg/t of product
8	Specific NO <sub>x</sub> emissions	kg/t of product
9	Specific SO <sub>x</sub> emissions	kg/t of product
10	Energy used from Renewable Sources	%
11	Energy used from Fossil Fuels	%
KPI No.	Proposed Operational KPI	Unit
12	Raw Materials Used	kg/t
13	Specific Fuel Consumption	kWh/t
14	Specific Electricity Consumption	kWh/t
15	Overall Equipment Efficiency (OEE)	%
16	Maintenance & Repair	%

The lab-scale activities focus on determining values for KPIs #1, #6 and #14 (see Table 2 to Table 5) due to the fact that the lab-scale equipment is not suited for the measurement of the remaining KPIs. The excluded KPIs are more relevant for industrial-scale processes. The results from the LCA cover the CO<sub>2</sub> related KPI.

## 3. Experimental results

The scope of the DAPhNE project is the development of the MW technology for high temperature processes. Concerning a fair and reliable comparison of this newly developed technology against the conventional technology, being under development for years, this paper focuses on lab-scale measurements concerning the materials ceramic frits and metakaolin.

The purpose of the ceramic frits production process is to obtain a vitreous material from its powder state that is insoluble in water by melting the raw material at 1200°C and subsequent cooling of the material. In total or partial replacement of traditional heating, the MW technology can only be applied in melting, since this is the only stage with high energy requirements for ceramic frits production, by using the cavity as a shaft furnace with a boron nitride tube. Material inlet and outlet are controlled in a way that a liquid pool can be formed in the tube, if sufficient MW energy is supplied.

The metakaolin processing consists of the calcination of the powdery caolin at 650°C achieving a very reactive metastable phase with pozzolanic properties [5]. In total or partial replacement of traditional heating, the MW technology can be applied in drying and calcining steps for metakaolin production, by using the cavity as a furnace with a rotary tube made of fused silica.

### 3.1. Development of lab-scale prototype

Figure 1 depicts the lab-scale MW system developed for the KPIs evaluation. It includes a MW power supply, which powers a 2.45 GHz magnetron. The isolator is intended to protect the source from MW energy, which may be reflected back from the applicator to the source for any reason, avoiding in that case the failure of the source. A high power reflectometer is included to provide on-line measurements of incoming and reflected power in the system, giving an estimation of the characteristics of the furnace load. The MW energy generated by the source is conducted through MW waveguides and introduced by means of a coupling network into the MW applicator. This is the heating chamber, where MW energy heats the material to be processed and is made of MW reflective materials responding as a cavity resonator. Thus, MW energy entering this chamber reflects at the walls and interacts with the material leading to an increase of its temperature. The design is optimized with regard to a high electric field strength at the position where the material is placed; adjustable coupling and tuning structures are implemented in order to match the different material characteristics.

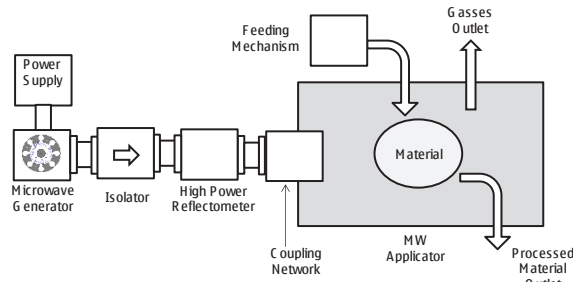


Figure 1: Lab-scale microwave system developed for the KPIs evaluation.

After being exposed to the MW energy, the material is discharged through an opening. The chamber is provided with an exhaust port, to facilitate the removal of exhaust gases generated by the heating of the material. The MW applicator is provided with inspection ports to allow temperature control during the heating process. Each open port has a filter to avoid MW leakage from the chamber.

### 3.2. Experimental results of innovative MW process

For ceramic frits the raw material in powder form is heated from room temperature up to 1200°C in 20 minutes. The MW output is slowly increased from 400 W to 1400 W until a liquid pool is formed. During heating, the cavity temperature is monitored via thermocouples to ensure safe operation conditions within the given material parameters. Material inlet and outlet are monitored with pyrometers. A continuous process is reached, resulting in a material output of 1.6 kg/h and a specific energy consumption of 793.5 kWh/t. This value has to be corrected by a factor of 2.0 [6] depending on the MW output since experiments showed, that the used magnetron has a very low efficiency compared to a magnetron with lower operating hours (see Table 2).

With regard to metakaolin, the raw material in powder form is heated from room temperature up to 650°C. The MW output is slowly increased from 400 W to 1000 W until the target temperature and a continuous process is reached, resulting in an output of processed material of 4.1 kg/h.

Table 2: Microwave (MW) lab-scale Key Performance Indicators (KPIs) for ceramic frits (CF).

KPI MW	Unit	KPI value
Specific Electricity Cost	€/t	74
Specific net CO <sub>2</sub> Emissions	kg/t	427
Specific Electricity Consumption	kWh/t	794

Table 3: Microwave (MW) lab-scale Key Performance Indicators (KPIs) for metakaolin (MK).

KPI MW	Unit	KPI value
Specific Electricity Cost	€/t	34
Specific net CO <sub>2</sub> Emissions	kg/t	144
Specific Electricity Consumption	kWh/t	360

The specific energy consumption of 360.2 kWh/t has to be corrected by a factor of 2.2 [6] depending on the MW output due to the low efficiency of the magnetron (see Table 3).

### 3.3. Experimental results of conventional process

Initial ideas aimed for the implementation of conventional heating systems in the cavity in order to have nearly the same operating conditions. Due to the high temperatures needed and the material properties of the cavity this idea had to be ruled out, since the cavity would not have been able to withstand the required temperature levels. Furthermore, it was expected that a heating system with the needed high power density could not be fitted in the cavity.

Since no furnace for continuous operation was available on short notice within the project, it was decided to perform trials based on batch processes but calculated for continuous processes, in order to get representative KPIs. This deemed to be the best comparable solution.

The calculation consists of two steps. The needed electrical energy for heating the empty furnace is measured and compared against the electrical energy needed to heat the furnace and the sample. Afterwards the furnace is set to hold the temperature in order to estimate the heat losses during continuous operation in steady state. The needed specific energy of the sample could be calculated by subtracting the energy needed for the empty furnace from the energy needed for the furnace and the sample.

For ceramic frits the raw material in powder form is heated from room temperature up to 1200°C in 6 hours. The temperature is held for 10 minutes. During the process a total of 38.0 kWh of electrical energy is consumed. By subtracting the energy needed for the test runs with the empty furnace (37.0 kWh) the energy consumption for the processing of the material can be calculated to 1.1 kWh with 0.6 kg of processed material. This results in a specific energy consumption of 1796.3 kWh/t. Previous tests showed that the furnace has a heat loss of about 3.8 kW when operated continuously at 1200°C. Under the assumption of a processing time of 10 minutes for 6 kg of processed material the specific electricity consumption results in 1900.4 kWh/t (see Table 4).

Table 4: Conventional (CONV) lab-scale Key Performance Indicators (KPIs) for ceramic frits (CF).

KPI CONV	Unit	KPI value
Specific Electricity Cost	€/t	177
Specific net CO <sub>2</sub> Emissions	kg/t	869
Specific Electricity Consumption	kWh/t	1900

Table 5: Conventional (CONV) lab-scale Key Performance Indicators (KPIs) for metakaolin (MK).

KPI CONV	Unit	KPI value
Specific Electricity Cost	€/t	31
Specific net CO <sub>2</sub> Emissions	kg/t	134
Specific Electricity Consumption	kWh/t	336

For metakaolin the raw material in powder form (kaolin) is heated up to 650°C within 3 hours with a soaking time of 10 minutes. The prior examination of the energy consumption revealed that the empty furnace would need 12.6 kWh of electrical energy to achieve this. For 0.5 kg of the processed material the furnace needs 12.8 kWh of electrical energy; thus leading to the specific energy consumption of 294.3 kWh/t. For the furnace in steady state the losses amount to 1.5 kW. Assuming a processing time of 10 minutes for 6 kg of processed material the specific electricity consumption results in 336.0 kWh/t (see Table 5).

### 3.4. Evaluation of experimental results

The accuracy of the examined parameters is limited by the reproducibility of the boundary conditions for both lab-scale processes as well as by the manual control of the MW process. Nevertheless, a comparison between microwave and conventional lab-scale measurements shows clearly the potential for savings in emissions and energy for the MW concept; at least for the case of ceramic frits. In particular, the specific electricity consumption is reduced by 58%, while CO<sub>2</sub> emissions are decreased by 51% (see Table 2 and Table 4). The difference can be assigned to fixed CO<sub>2</sub> emissions from carbon introduced by raw materials. As regards metakaolin, no large differences are observed (Table 3 and Table 5) in specific emissions and electricity consumption; possibly due to the lower process temperatures (650°C versus 1200°C for ceramic frits).

With the different energy transfer mechanisms considered (convective heat transfer and thermal radiation versus heat production in the material), CONV heating is subjected to high thermal losses compared to MW heating and therefore, especially for high temperature applications, it is less energy efficient. Lab-scale tests indicate a prospective emission and energy saving of the MW furnace. In order to approach a more realistic comparison versus industrial reference data, a preliminary LCA was conducted, focusing on CO<sub>2</sub> emissions and its corresponding impact category (global warming potential). The following section provides the modeling details and the corresponding results.

## 4. LCA results

Life cycle assessment [7-10] is a methodology aiming to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment as well as to identify and evaluate opportunities to bring about environmental improvements. The International Standard ISO 14040-4 provides the methodological framework for LCA applications, as well as the definitions of the four main LCA phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, (4) interpretation.

### 4.1. Goal and scope definition

The main purpose of the LCA study is to assess the environmental impact of the innovative MW production

process, both in terms of KPI values, which are associated to common industrial practice, as well as relevant environmental impact categories. The obtained results are compared with corresponding results regarding an equivalent conventional production process in order to highlight and justify the environmental benefits of the MW system. Therefore, the results are expressed both in impact category (kgCO<sub>2-eq</sub>/t) and KPI (kgCO<sub>2</sub>/t) units with a functional unit of 1 ton of product (ceramic frits and metakaolin).

Generally, the manufacturing processes of the two materials investigated include three main processes: i) Upstream processes, which include grinding and preparation of the raw materials, ii) Main processes, which include calcining and melting of the raw batch and iii) Downstream processes, which include quenching and milling processes for ceramic frits and metakaolin materials, respectively. Regarding the system boundaries, two approaches are followed, according to the type of LCA result. For the calculation of the impact categories, the system boundary includes only the ii) Main processes CONV and MW (see Figure 2), while upstream and downstream processes are excluded from the calculation of impact categories due to the fact that they represent common life cycle phases to all materials, contributing with the same environmental impact.

As regards the calculation of the “LCA enhanced” KPI, results of specific emissions are distinguished in direct and indirect, according to the location of the source. Direct gate-to-gate-emissions are mainly due to raw material input (materials) and combustion of fossil fuels during the process. On the other hand, indirect emissions are emitted outside the processing facility and include central electricity generation and extraction, transportation of raw materials as well as extraction and transportation of fuels.

Moreover, the major assumptions are described as follow, considered necessary while performing the LCA:

1. The CONV production processes are treated as industrial-scale, while the MW processing is considered as demo-scale, since a MW system has not yet been implemented in large-scale production lines. Therefore, the two concepts may not be directly comparable; however the lab-scale data is the best available compromise in view of an industrial MW process;

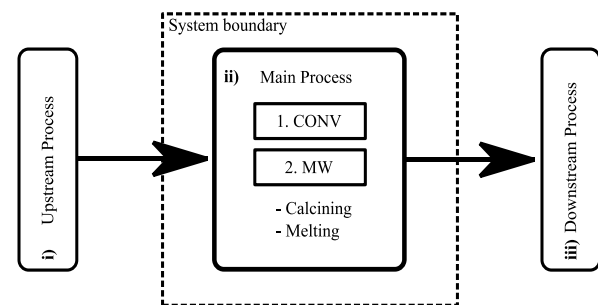


Figure 2: System boundary for calculation of impact categories for conventional (CONV) and microwave (MW) processes.

2. A simple MW system model is developed for calculating “LCA enhanced” KPIs in a suitable LCA software (SimaPro 7.3), making various assumptions concerning the materials and dimensions of the system components;

3. Assuming that the demo-scale capacity amounts to 10 kg/h and a yearly operation of 6000 h/year for a lifespan of approximately 20 years, it was estimated that 0.00083 pieces of “MW system assembly” are needed for the production of 1 ton of ceramic frits and metakaolin;

4. Recycling of materials for infrastructure or other end-of-life scenarios have not been examined.

#### 4.2. Life cycle inventory (LCI)

The inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system assessed. Data used in the LCI concerning CONV ceramic frits and metakaolin production are provided by DAPhNE partners and data concerning MW thermal treatment derived from lab-scale experimental analysis.

Due to confidentiality reasons, primary data regarding the KPI values of the conventional processes cannot be disclosed. Secondary data are retrieved from databases available in SimaPro 7.3 LCA software package and used for the inventory analysis. The commercial database Ecoinvent 2.2 [11] has been primarily utilized, due to being well known for its reliability, transparency and independency.

Generally, the use of the secondary data in the inventory phase introduces several uncertainties in the LCA results. In order to reduce these uncertainties and improve the accuracy of the results, relevant data have been modified on the basis of the information and practices of European suppliers and manufacturers as well as DAPhNE partners.

#### 4.3. Life cycle impact assessment (LCIA) - results

The environmental comparison analysis of the CONV and MW processes is performed for both materials investigated, considering not only impact categories but also industrial KPIs.

According to EN 15804:2012 [12] several environmental indicators should be considered in the LCIA phase, such as global warming potential (GWP), acidification and eutrophication. In the present study, only the GWP indicator is considered, since the CO<sub>2</sub> emissions represent the major environmental issue of the CONV manufacturing process of both materials. The IPCC 2007 GWP 500a Impact Assessment Method is used for the LCIA phase [13]. Moreover, the LCA results are used to derive a “LCA enhanced” KPI for the newly developed MW technology.

In order to show the effect of the electricity mix used, two scenarios are examined: utilization of EU-27 (Scenario 1) and Swiss electricity mix (Scenario 2). The Swiss case has been considered due to being one of the less “carbon intensive” throughout Europe.

##### 4.3.1. Ceramic frits (CF)

The CONV process exhibits the highest environmental impact in the GWP categories for both scenarios analyzed. In particular, in this category, the MW process shows an environmental impact 50% and 65% lower than the impact of the CONV process in Scenario 1 and Scenario 2, respectively (Figure 3). This result is influenced by the higher amount of direct CO<sub>2</sub> emissions related to the CONV process (process heat from combustion of fossil fuels). In addition, the lower environmental impact of Scenario 2 is also due to the electricity data considered.

An important issue in the case of ceramic frits is the direct CO<sub>2</sub> emission assigned to the composition of raw materials. In particular, the carbon input of different raw material components (such as calcium carbonate and dolomite) causes a significant contribution. The CO<sub>2</sub> arising from raw materials is inevitably emitted also in the MW system case.

In any case, as shown in Figure 4, the MW technology achieves considerable CO<sub>2</sub> reductions, ranging from 20% up to 58%. Differences between the reduction percentages shown in Figure 3 and Figure 4 can be assigned to the composite character of the GWP index, which is heavily affected not only by CO<sub>2</sub>, but also from CH<sub>4</sub> emissions.

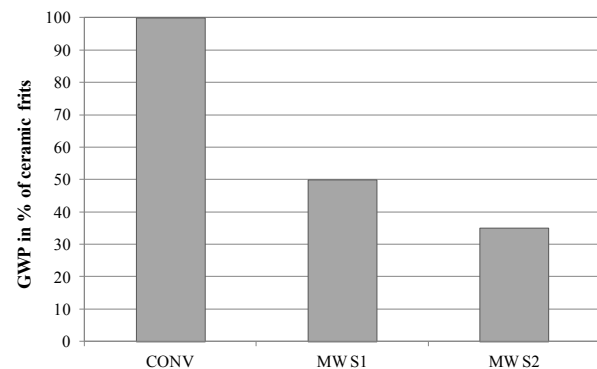


Figure 3: Results of the Global Warming Potential (GWP) for ceramic frits: Conventional (CONV) and microwave (MW) processes; Scenario 1 (S1) (EU-27), Scenario 2 (S2) (Switzerland).

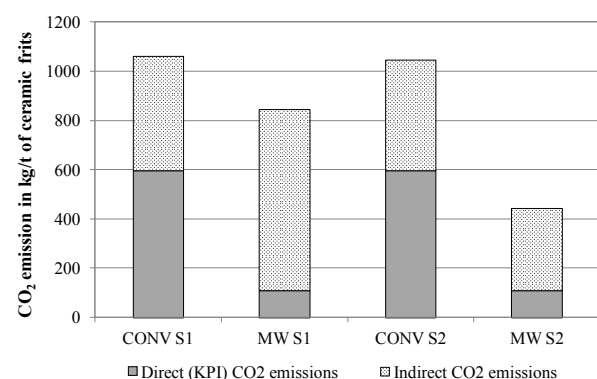


Figure 4: Direct and indirect CO<sub>2</sub> emissions for ceramic frits: Conventional (CONV) and microwave (MW) processes; Scenario 1 (S1) (EU-27), Scenario 2 (S2) (Switzerland).



#### 4.3.2. Metakaolin (MK)

In all energy scenarios investigated for metakaolin, the conventional process exhibits higher environmental impact, especially with regard to the GWP (Figure 5).

In particular, the MW process in Scenario 1 shows a GWP impact 25% lower than the relevant index of the CONV process. In particular, the environmental benefits of the MW process are mainly justified by the fact that MW processing features zero direct CO<sub>2</sub> emissions. In Scenario 2, the environmental impact of the MW process is decreased by 50%.

As regards the KPI related results, Figure 6 shows a reduction of 17% of total CO<sub>2</sub> emissions. Nevertheless, the MW system features an increase of indirect CO<sub>2</sub> emissions due to electricity consumption, since the amount of electricity consumed (360 kWh/t) is greater than the corresponding electrical demand in the CONV process. Considering a “cleaner” electricity mix, the relative decrease of total CO<sub>2</sub> emissions is higher and results in a total reduction of 38% for Scenario 2.

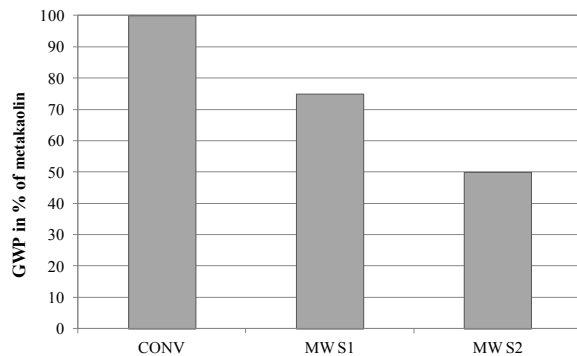


Figure 5: Results of the Global Warming Potential (GWP) for metakaolin: (CONV) and microwave (MW) processes; Scenario 1 (S1) (EU-27), Scenario 2 (S2) (Switzerland).

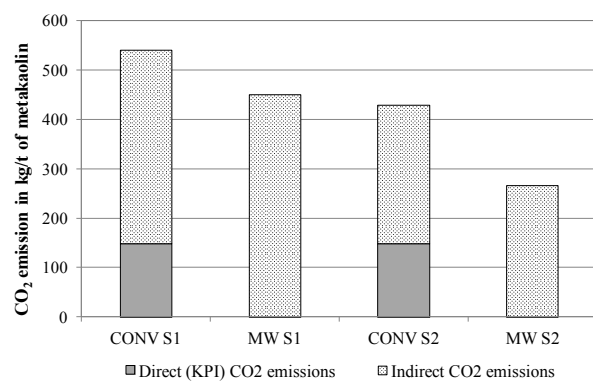


Figure 6: Direct and indirect CO<sub>2</sub> emissions for metakaolin: conventional (CONV) and microwave (MW) processes; Scenario 1 (S1) (EU-27), Scenario 2 (S2) (Switzerland).

## 5. Conclusion

The scope of this paper is the implementation of a new KPI methodology aimed towards industrial needs, especially with regard to CONV and MW heating technologies in energy intensive processes. Experiments and LCA based modeling are carried out for validation purposes and support the methodology. The potential introduction of MW heating systems in industrial applications clearly displaces emissions outside the processing facility boundary. Direct emissions are turned to indirect by avoiding fossil fuel combustion for heat generation and incorporating a “full-electric” process. As shown in the preliminary LCA results and KPIs definition herewith presented, the MW system exhibits a definite carbon emission reduction potential, provided that the MW process achieves a reduction in terms of process energy demand and the MW electric feed is not predominantly provided by fossil fuelled power plants, featuring a low carbon load. Future work will be focused on data from industrial scale MW and CONV high-temperature applications.

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